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WHY IS THERE MOTION IN OUR WORLD?

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Abstract

Is there asymmetry in physical processes? Does the physical world evolve toward its state of rest? If it does, why is there motion in our world now? – In this paper, I try to reconstruct to largely distinct answers to these ever exciting questions: (1) the antique answer given by Aristotle, the most influential 'scientist' in antiquity, and (2) the modern answer rendered by the thermodynamic and cosmological theories of our times. By comparing these answers, an attempt will be made to highlight some similarities and differences between them. I try to show that these problems belong, today as well as in Aristotle's 'pre-scientific' time, to the border region of physics and metaphysics. [1]

Keywords: history of physics, thermodynamics, cosmology, Heat Death, extropy.

1. An Ancient Problem Returns

Aristotle's physics is the most influential physical theory of antique science, and one of the most influential physical theories ever created. The birth of modern science in the seventeenth century is in part a result of the fight against the dogmatic devotion to the Aristotelian scientific mentality, and since then Aristotelian physics has been usually condemned and ridiculed. Before very lately, not many historians of science realised that Aristotle's physics seems to be much more coherent and favourable if we take it out of the context of modern (Newtonian) mechanics, to which it is always compared, and try to see it in its own right [7]. The traditional interpretation is that Aristotle's theory of nature was based mostly on a priori philosophical considerations, and less on empirical observations, therefore it was natural philosophy rather than natural science. Today, however, it is becoming more and more acknowledged that Aristotle's physics is a relevant non-mathematical theory of nature, and that its primary concern is not the set of phenomena that mechanics aims to explain. It seems reasonable to work under the assumption that Aristotle was mostly interested in natural phenomena that are discussed today within the field of thermodynamics [9].

In Aristotle's physics, the problem of Heat Death (as we call it today) is recognised and dealt with, although the way he tackles the question is somewhat

[1] An earlier version of this paper is about to appear in *Open Systems and Information Dynamics*

alien to our modern mind. For the sake of reconstruction, I will make an analogy between his ideas and the respective theses of modern physics. Aristotle's views can be summarised briefly as the following: *every natural body has its natural place to which it has a tendency to get if no external process prevents it* [11]. (More precisely, this principle concerns the elements consisting the bodies, and not the bodies themselves, but the above law can be considered as a consequence of the principle, where 'place' is understood in a broader sense than the modern concept of unique spatial location.) This principle raises the following question: Why is there motion in the world, if systems tend toward their 'rest' states? As Aristotle puts it:

> 'a baffling problem – viz. why the simple bodies, since each of them is travelling towards its own place, have not become dissevered from one another in the infinite lapse of time.' [3]

On the other hand, a very similar problem appeared in the nineteenth century with the introduction of the second law of thermodynamics. As the analogy goes, in today's thermodynamics it holds that *every thermodynamic system has its equilibrium state to which it has a tendency to get if no external effect prevents it*. This law was conceptually (although not logically) inconsistent with Newtonian mechanics, the dominant physical theory of that time, since it states that the direction of natural processes is not indifferent. If we extend the validity of the second law to the whole universe as one global thermodynamic system, then we find ourselves in the same situation as Aristotle did: we need to give an explanation to the dynamic, instead of static state of the universe. Rudolf Clausius introduced the concept of Heat Death with the following words:

> 'The more the universe approaches this limiting condition in which the entropy is a maximum, the more do the occasions of further changes diminish; and supposing this condition to be at last completely obtained, no further change could evermore take place, and the universe would be in a state of unchanging death.' [6]

In this paper I would like to discuss two very different solutions to the problem given by ancient and modern physics, although I will put a greater emphasis on the modern theory which I discuss in more details. I hope that this case study can tell us as much about today's cosmological theory as it suggests about the nature of scientific change.

2. The Antique Solution

Aristotle's natural world was divided into two regions: *the sublunary region* (consisting of the four material elements of mundane bodies), and *the superlunary region* (consisting of the fifth element of celestial bodies). 'Physics', or the 'study of nature', was supposed to deal with sublunary phenomena, while the region of celestial spheres was governed by eternal 'metaphysical' laws. This fundamental distinction between the two regions of the universe was rigidly sustained in the Aristotelian science of the Middle Ages. According to this picture, our initial problem (of 'Heat Death') is relevant only to the natural (sublunary) phenomena. However, Aristotle's final solution did appeal to the eternal celestial world as well, and therefore it can be reconstructed in two stages:

1) The sublunary stage. It is the circular motion of the Sun which constantly induces processes in nature, partly by maintaining the transformation of elements one into another, and therefore by displacing bodies from their natural places:

> 'For the sun as it approaches or recedes, obviously causes dissipation and condensation and so gives rise to generation and destruction. Now the earth remains but the moisture surrounding it is made to evaporate by the sun's rays and the other heat from above, and rises. Vapour cools because its heat is gone and because the place is cold, and condenses again and turns from air into water. And after the water has formed it falls down again to the earth. […] So we get a circular process that follows the course of the sun.' [2]

It is worth mentioning that this quote eloquently illustrates why most of Aristotle's physics can be interpreted as some sort of proto-thermodynamics, rather than proto-mechanics. His explanations very often appeal to the four mundane elements (earth, water, air, fire), and they lead to a great number of discussions about heat phenomena.

2) The superlunary stage. In spite of the 'irreversibility' of Aristotle's natural processes, the eternal motion of natural bodies (contrary to their 'nature') is maintained by the eternal motion of celestial spheres (inherent in them), namely that of the Sun's sphere. For as the Sun is moving around the Earth, it constantly changes the heat conditions of natural processes. Thus, postulating this inherent eternal motion of the spheres would suffice for the purpose of answering the original question concerning motion of natural bodies. But Aristotle continues his chain of causation. The motion of the Sun's sphere is brought about by the motion of outer spheres (each of them causing the inner neighbour to move), and the motion of the outmost sphere is caused by the First (or Unmoved) Movent.

> '[…] for it is impossible that there should be an infinite series of movents, each of which is itself moved by something else, since in an infinite series there is no first term – if then everything that is in motion is moved by something, and the first movent is moved but not by anything else, it must be moved by itself.' [4]

This is a purely a priori argument concerning the chain of causation: if all bodies are moved by other bodies then, at the beginning of this chain, there must be an actor that moves but is not moved. (As many ancient Greek thinkers, Aristotle was against, and could not accept, the notion of infinity.) That this First Movent must be located at the outmost heavenly sphere, is 'proved' in the following way:

> 'Moreover the [first] movent must occupy either the centre or the circumference, since these are the first principles from which a sphere is derived. But the things nearest the movent are those whose motion is quickest, and in this case it is the motion of the circumference that is the quickest: therefore the movent occupies the circumference [of the world].' [5]

This is in part another a priori argument, although it appeals to the observation that bodies which are directly caused to move are quicker in their motion than bodies caused to move indirectly (or in a mediated way). Aristotle's physics is based, on the one hand, on the observation of everyday phenomena (where friction and dissipation are always present, unlike in Newton's 'ideal cases' where conservation laws can be formulated) and, on the other hand, on more general philosophical principles about nature and being. Physics and metaphysics are not separated in ancient theories of nature; but are they separated in modern physics?

3. The Modern Solution

The nineteenth century problem of Heat Death was taken its sting out in the twentieth century, with the birth of modern cosmology. Since the expanding universe is not an eternal entity, there is no direct contradiction between the universal validity of the second law of thermodynamics and the empirical evidence of natural processes. Even if the final state of Heat Death is unavoidable, since the past history of the universe is finite, there is nothing paradoxical in that we have not reached this state yet: it will happen some time in the future. The so-called 'Heat Death paradox' is thus resolved.

However, this solution raises another problem: if the preferred state of systems is equilibrium, why are they not in their equilibrium state today? What happened in the past course of cosmic development which can be called for explaining this non-equilibrium picture of the world? In other words, our initial question is still valid: Why is there motion in Nature? Or more precisely: Where does the existing motion originate from?

3.1. Extropy

In order to formulate the question in a language which is more suitable for modern scientific purposes, let us introduce the notion of *extropy* [10]. It is a state parameter which expresses the distance of a system from its equilibrium state on the entropic scale. In other words, it measures the entropy production of the imaginary process that takes the system to equilibrium with the environment. It is the difference between the maximal entropy of system plus environment and the actual entropy of system plus environment:

$$\Pi = S_e^r + S_e^k - S^r - S^k. \tag{1}$$

In the case of the universe, the 'environment' does not exist (since the universe contains all entities that can be expressed in the physical language), so the extropy of the universe is expressed in a slightly different form:

$$\Pi^U = S_e^U - S^U. \tag{2}$$

A system is in equilibrium if its extropy is zero: in the case of the universe, this is what we call 'Heat Death'. Our question therefore can be formulated in the following way: What process can produce global extropy in the cosmic scale?

3.2. The Model Universe

Let us regard the universe as a system which is determined by three extensive state parameters [1]:

1. For R:
$$\frac{1}{2}\dot{R}^2 = \frac{G}{R}\left(\frac{4\pi}{3}R^3\rho\right) + \kappa, \tag{3}$$
where R is the 'radius' of the universe (the scale parameter), G is the gravitational constant, ρ is the matter density, and κ is a constant that determines whether the universe is open ($\kappa \geq 0$) or closed ($\kappa < 0$).
2. For E:
$$\dot{E} + p\dot{V} = 0, \tag{4}$$
where E is the internal energy of the universe, p is the pressure, and V is the volume (proportional to R^3). We can see here that the internal energy is not constant because it is transformed into the energy of the gravitational field: this is a peculiar feature of the universe as a thermodynamic system.
3. We have a third extensive parameter in the description: N is the number of particles in the universe. Unlike in the case of the other two extensive parameters, we suppose that N is constant.

In this model universe we assume the presence of two matter components: atomic hydrogen and black-body photon gas, both homogeneous and isotropic. We assume that these components must cool as the universe expands. However, the cooling rates of the two components obey different laws: the baryonic matter would cool according to R^{-2}, while the photon gas would cool according to R^{-1}, if the only thermodynamic process present was the expansion of the universe. In other words, the temperatures of the components tend to be different, and there is a process of heat flow from the hotter to the cooler component. In our model universe, the strength of this interaction is given as an arbitrary numerical value (considered to be constant).

We can now derive a system of differential equations (given in [1]) which, assuming that the radius changes according to *Eq.* (3) above, enables us to determine the behaviour of the following state parameters of the system: R, the radius of the universe; T_g, the temperature of the gas component; T_r, the temperature of the radiation component; and S, the total entropy of the universe. The system of equations is the following:

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{2c}{R^2} + 2c_1\gamma T_r^4 + \gamma BR^{-3}(2m + 3T_g), \tag{5}$$

$$\frac{\dot{T}_r}{T_r} + \frac{\dot{R}}{R} = \frac{1}{4c_1} ABT_r^{-1}R^{-6}(T_g - T_r), \tag{6}$$

$$\frac{\dot{T}_g}{T_g} + 2\frac{\dot{R}}{R} = \frac{2}{3} AT_r^3 T_g^{-1}(T_r - T_g), \tag{7}$$

$$\dot{S} = ABR^{-3}T_r^2 T_g^{-1}(T_r - T_g)^2, \tag{8}$$

where B is the baryonic number, m is the molecular mass, A is the coefficient of the interaction, C_g and C_r are the heat capacities of the gas and radiation components, respectively, c and c_1 are constants, and the rest has been explained above.

Given the values of the parameters yielded by the solution of the system of equations, we can easily calculate the extropy function of the model universe. That is, we calculate the amount of entropy the system would produce by getting to equilibrium at a given instant of time. Provided that the heat capacities are constant, the expression of the extropy is:

$$\Pi = (C_r + C_g) \ln \frac{T_g + DT_r}{(1 + D)T_g^{\frac{1}{1+D}} T_r^{\frac{D}{1+D}}}, \tag{9}$$

where $D = C_r/C_g$.

The development of the model universe was simulated numerically by the program *Mathematica*.

3.3. Evolution of the Model Universe

We have to distinguish between two qualitatively different cases: If the universe is open ($\kappa \geq 0$) then the expansion will continue for ever (because the gravity of the massive matter is not strong enough to stop it) and the universe has an infinite future; but if it is closed ($\kappa < 0$) then the expansion will stop and turn to contraction, by the end of which the history of the universe is finished. The evolution paths of state parameters belonging to an open universe are plotted in *Fig. 1*, while the case of a closed universe is shown in *Fig. 2*.

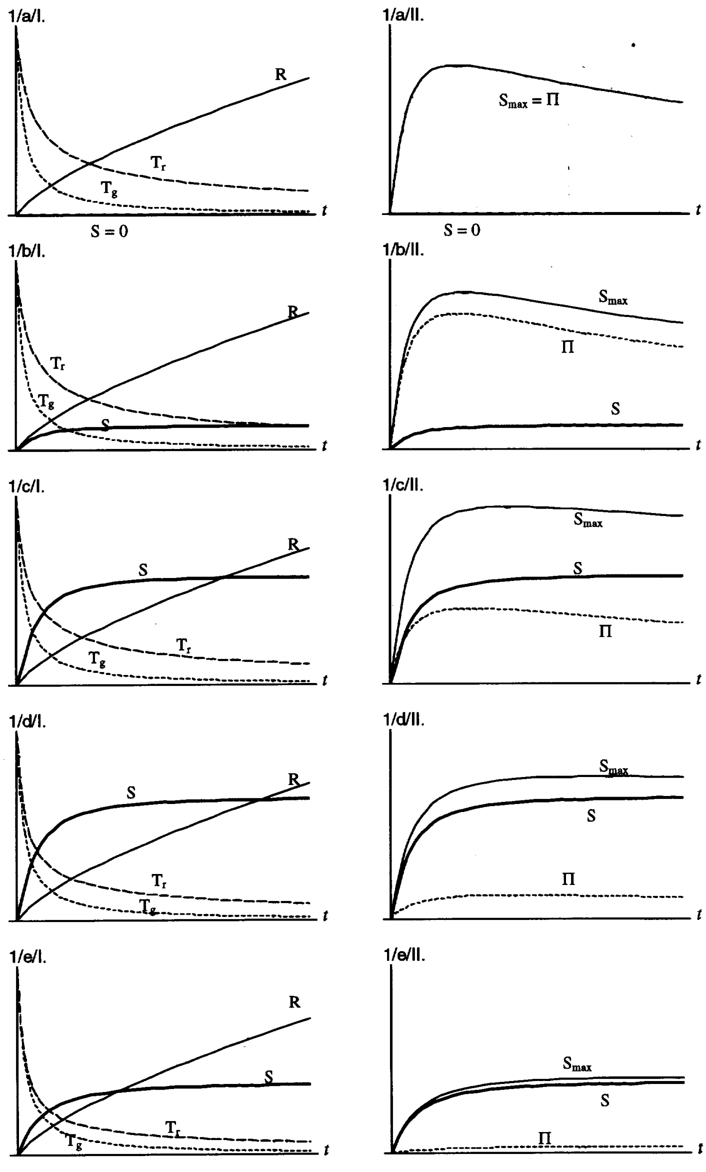

Fig. 1. Thermodynamic functions in an open universe

On the left side of the figures you can see the graphs of the radius, the temperatures of components, and the entropy. On the right side you find entropy, extropy, and the maximum value of entropy ($S_{\max} = \Pi + S$) belonging to the equilibrium state at the given extensive parameters. We increase the strength of the interaction

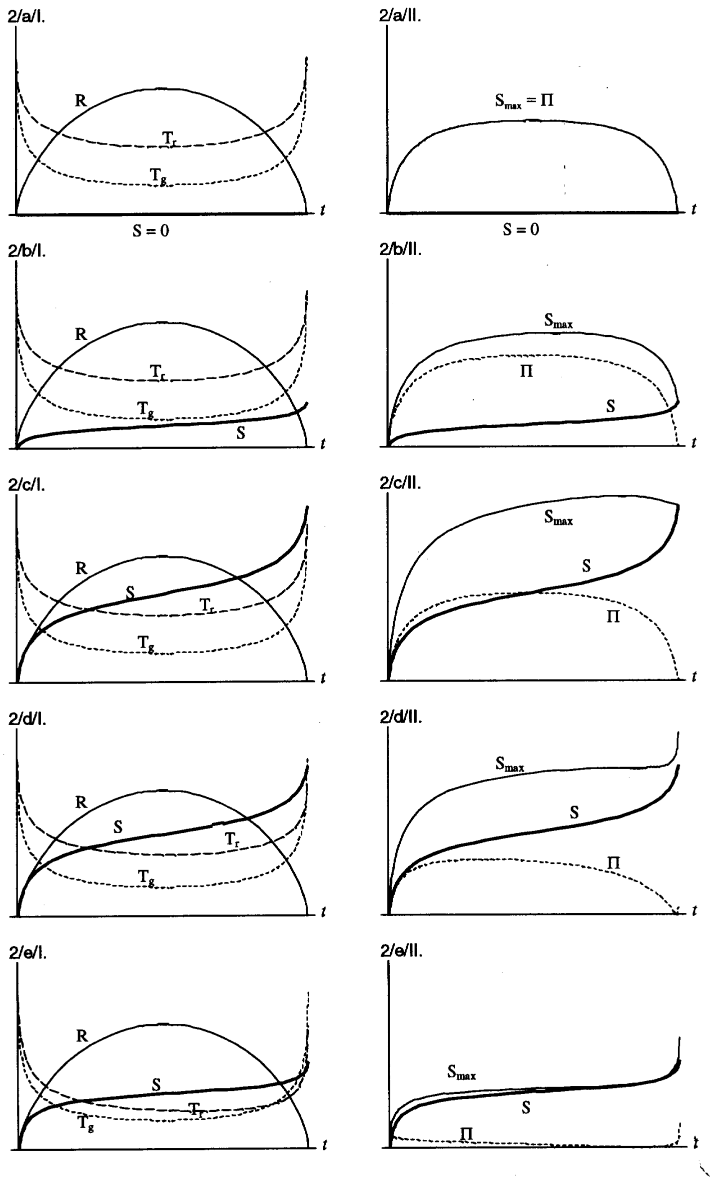

Fig. 2. Thermodynamic functions in a closed universe

between the components (A) from the top figures towards the bottom ones, the value being 0 in the first case and very large in the bottom case.

Let us concentrate on the case of open universe first. We see that two factors put a constraint on the value of entropy: if the interaction is weak, there is obviously not much entropy produced; in the case if the interaction is strong, the temperature difference is small, so the interaction process becomes weak again. There is an optimum case for entropy production when the universe is the most ‘active’ thermodynamically. Nonetheless, extropy behaves in a different way: the dependence of extropy on the strength of interaction follows a monotonous function. The stronger the interaction is, the smaller the extropy becomes, and the closer the system gets to equilibrium.

Let us now turn to the time-dependence of the parameters. We can see that no matter how strong the interaction is, the extropy function follows the same qualitative route with time: it increases at the beginning (until the temperature difference becomes maximal), but then it starts to decrease and tends to zero as time approaches infinity. It means that, in our open model universe, there is no way of avoiding the final state of Heat Death, which is the boring state of absolute, eternal smoothness and peace. Still, thanks to the expansion of the universe, the temperatures of the two components become different vehemently at the beginning, at the very early stages of cosmic history. Therefore, there is an initial increase in the value of extropy as it becomes greater than zero and the universe leaves its equilibrium state. Thus the expansion of the universe creates the possibility of all the physical processes of the future. To put it very simply, extropy means process in physical systems.

In the case of a closed universe, Heat Death becomes a marginal problem: since the future of the universe is finite, the equilibrium state may or may not occur before the end. But it is important to notice that equilibrium in a contracting universe is *not* an endless state of Heat Death, but it is a momentary phase. As the components, owing to the contraction, start to warm up again the temperatures get closer one to another. But if the interaction is not negligible then the contraction is not symmetrical to the expansion, because the direction of the heat flow does not turn back when the collapse begins. As a consequence, the plots of the two temperatures cross each other before the end, and this results in an immense final extropy increase. Just before the very end of everything, the universe becomes ‘active’ again for a short while.

3.4. Beyond the Model

Of course, if we want to give a more accurate answer to the question whether Heath Death will occur or not, we have to transcend the limits of our simple model. As we saw, the problem of Heat Death is relevant only in an open universe, so in this section I will constrain myself to this case and suppose that the universe has an infinite future.

Let us first turn to the assumption that the components are homogeneously distributed. While the $2.7K$ background radiation (the photon gas) is proved to be practically homogeneous indeed, baryonic matter is condensed into different material structures discontinuous one from another: stars, galaxies, clusters of galaxies, etc. Condensation increases internal energy in these dense regions of matter, and thus baryonic structures is significantly hotter than the photon gas are born. However, these structures radiate their heat surplus into the photon gas (bringing about small inhomogeneities in it), and even if this radiation process is enormously lengthened by nuclear reactions inside stars as sources of heat, this temperature reversion between regions of the two components is only a temporary phenomenon. All stars – in fact all condensations of baryonic matter – must live up their energy supply sooner or later. Even black holes, first thought to violate the second law of thermodynamics, evaporate through quantum gravity effects and therefore have a finite, although sometimes very long, life span before they disappear. From the viewpoint of Heat Death, the present inhomogeneous picture of the universe, as we know it today, is but an incidental contingency.

Another oversimplification of our model is that it considers only two components. But there seems to be only one significantly massive component in addition to the two already discussed ones: the neutrino gas. This follows the same cooling rate as the photon gas does, although they are not in equilibrium (the photon gas was heated by the $e^+ - e^-$ annihilation at the very early stages). The neutrino gas, however, does not interact with the photon gas, and its interaction with the baryonic matter is also very weak, so its expansion is practically adiabatic: it plays hardly any role in the overall thermodynamic picture of the universe. Furthermore, the qualitative results derived from the model do not change even if there are more components present: all the temperatures are ever decreased by the expansion of the universe. Concerning the future of the two known components, protons, as we know it today, have a finite life span and after their decay the free neutrons will disappear almost immediately. In other words, baryonic matter will vanish from the universe. Whether neutrinos will remain forever or they will decay too is not determined yet but, as we have seen, they do not matter much from the viewpoint of Heat Death.

Having mentioned the early stages of the universe, let us examine how phase transitions of matter can influence our results. When the temperature of the universe drops below a value $T_x = m_x c^2/k$, where m_x is the mass of a certain type of particle, then this particle enters into its non-relativistic phase and realises a new material component in the universe (e.g. quarks–antiquarks, neutrinos–antineutrinos, electrons–positrons). Now, this phase transition clearly increases the global entropy of the universe [8], but how about extropy? The total entropy available for the whole system also increases (following simple considerations in statistical physics), and this increase is never smaller (and generally larger, except when the components contain equal numbers of particles) than the rise in actual entropy. That is, extropy grows in phase transitions: the universe gets further from thermal equilibrium.

Now, it seems today that the era when phase transitions occurred is long gone: this was the hot and dense state when events followed rapidly one after another. However, we do not know for sure if such drastic changes will not happen in the future, because particles with very small mass might appear at still lower temperatures. Still, we have a very good reason to suppose that there occurs (or occurred) once a last transition: since the universe is finite in mass/energy, there can only be a finite number of material components in it. Phase transitions cannot postpone Heat Death for ever.

Finally, we can see that the whole problem boils down to the following simple conceptual scheme applied in these cases: since the universe is a finite system there can be no infinite process whatsoever (known or unknown) that can keep it out of equilibrium state forever. But this is, as we can call it, a 'metaphysical' principle and, except for the finiteness of the universe, no empirical knowledge is embedded in it. In order to explain, through particular physical processes, why the universe will not escape final equilibrium we should examine from case to case an infinite number of conceivable possibilities and rule them out one by one, which is impossible. Again, metaphysical (or, more or less, normative) principles seem to 'intrude' unavoidably to our scientific knowledge.

4. Conclusion

We have seen two very different solutions to the problem why the observed 'activity' of nature does not contradict the irreversibility of physical processes. In the ancient case, Aristotle sacrificed the closedness of the universe and put a theoretical entity at the border of the world, which plays as an eternal source of motion. Today cosmological theory sacrificed the belief in an endless, eternal universe and postponed Heat Death into the indeterminate future, regarding the present picture of the world as contingent and temporary. However, modern theory cannot formulate certain claims about Heat Death: this question must be re-examined in the light of all newly discovered effects and processes. As a concept concerning eternity, Heath Death seems to belong, not so much to the field of our scientific knowledge, but to the horizon and limits of our prevailing theories about the universe.

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